Comparison of dimensional tolerance grades for metal AM processes

Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 88 (2020) 399–404

www.elsevier.com/locate/procedia

13th CIRP Conference on Intelligent Computation in Manufacturing Engineering, CIRP ICME '19

Comparison of dimensional tolerance grades for metal AM processes

Paolo Minetola[a,*], Manuela Galati[a], Flaviana Calignano[a], Luca Iuliano[a], Giovanni Rizza[a], Luca Fontana[a]

[a]*Politecnico di Torino, Dept. Management and Production Engineering (DIGEP), Corso Duca degli Abruzzi 24, 10129 Torino, Italy*

* Corresponding author. Tel.: +390110907210. *E-mail address:* paolo.minetola@polito.it

Abstract

Each manufacturing process produces geometric features with some dimensional errors from the ideal nominal geometry. The knowledge of the dimensional tolerances associated with the specific fabrication process is fundamental for choosing the proper sequence of finishing operations to meet the design requirements. While the ranges of dimensional tolerances for traditional manufacturing processes are well mapped in the literature, a little information is available for additive manufacturing (AM) techniques. In this paper, a benchmarking analysis is carried out between two different AM processes for metals and the dimensional accuracy of each AM machine is defined using the ISO IT grades of a reference artifact.

Peer review under the responsibility of the scientific committee of the 13th CIRP Conference on Intelligent Computation in Manufacturing Engineering, 17-19 July 2019, Gulf of Naples, Italy.

Keywords: Benchmarking; Accuracy; Selective laser melting; Electron beam melting; IT grades.

1. Introduction

When a component is manufactured, regardless of the production technique adopted, it will surely contain some dimensional errors deviating its final dimensions from the nominal geometry required by the engineer's design. These dimensional errors vary from a production technique to another. For traditional production processes, such as casting, turning or milling, the dimensional accuracy is well known, while little information is available for the new additive manufacturing (AM) processes or layerwise fabrication.

AM technologies are capable to produce prototypes or end-usable parts adding the material layer after layer [1]. The idea to produce a part layerwise is not recent but derives directly from the second half of the nineteenth century, when this production technique was adopted for the fabrication of photo-sculptures and topography maps [2].

The possibility to produce parts without the need for a specific tool or die empowers designers and engineers with great freedom. Through AM, the production of various parts having complex geometry can be completed using a single machine.

Although the early AM techniques were adopted for the production of polymeric prototypal parts, at present days several AM systems for the fabrication of end-usable metal parts are available on the market [3]. Unlike polymeric parts, metal components require tight dimensional and geometrical tolerances to meet the functionality requirements [4]. Therefore, metal parts often undergo finishing operations.

In order to select the finishing procedures that are necessary to meet the design requirements, it is important to know what is the precision grade that the specific production system is capable to reach. To this aim, the ISO standard International Tolerance (IT) grades [5] define the classification of the dimensional accuracy of a generic part. In the literature, only a few studies have been conducted to analyze the accuracy of AM metal systems capabilities. Moreover, most of these analyses do not consider the ISO system for the evaluation of the process accuracy.

In this work, the benchmarking of two different AM processes for metals is carried out on the basis of the previous

2212-8271 © 2020 The Authors. Published by Elsevier B.V.

Peer review under the responsibility of the scientific committee of the 13th CIRP Conference on Intelligent Computation in Manufacturing Engineering, 17-19 July 2019, Gulf of Naples, Italy.
10.1016/j.procir.2020.05.069

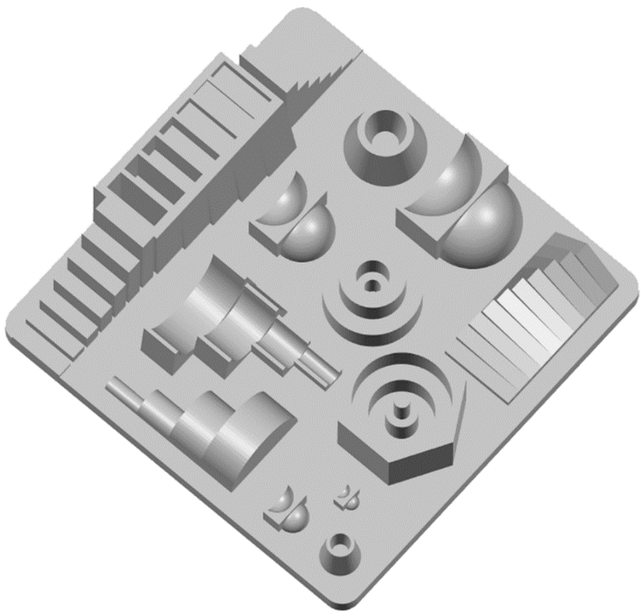

Fig. 1. Geometry of the reference part [6] available in Grabcad library [7] (Overall dimensions: 110 x 110 x 33 mm).

research activities that some of the authors recently developed for the evaluation of the accuracy of AM systems for polymeric materials [6, 8, 9].

The benchmarking study requires the adoption of a reference part (Fig. 1) proposed by Minetola et al. [5]. That reference part includes a high number of geometric features that cover the first eight ranges of ISO basic sizes: 1 to 3 mm, 3 to 6 mm, 6 to 10 mm, 10 to 18 mm, 18 to 30 mm, 30 to 50 mm, 50 to 80 mm and 80 to 120 mm.

The geometry of the reference part includes simple shapes in both concave and convex forms that are replicated with different dimensions that fit into different ranges of ISO basic sizes. The shapes were organized and located in order to evaluate geometrical tolerances among them, as well as form errors accordingly to the GD&T system.

The part geometry is downloadable for free as an STL file from GrabCAD library [7], so artifact replicas can be directly produced by means of any AM production system with proper build volume.

Up to date, this reference part has been adopted for benchmarking 3D printers for polymers only [6, 10, 11]. The innovative aspect of this work is that the same methodology proposed by Minetola et al. [6] is applied for the first time to two powder bed fusion (PBF) processes and machines for metal parts. Thus, this paper extends the comparison of the dimensional accuracy of AM systems and compares a wider range of additive technologies.

2. Compared AM systems

The first AM system for metal materials that is considered in this study is an Electron Beam powder bed fusion (EB-PBF) machine A2X (Fig. 2a) produced by Arcam AB (Sweden). The second system is a Laser powder bed fusion (L-PBF) machine EOSINT M270 (Fig. 2b) that was commercialized by EOS GmbH (Germany), but it is no longer on the market nowadays.

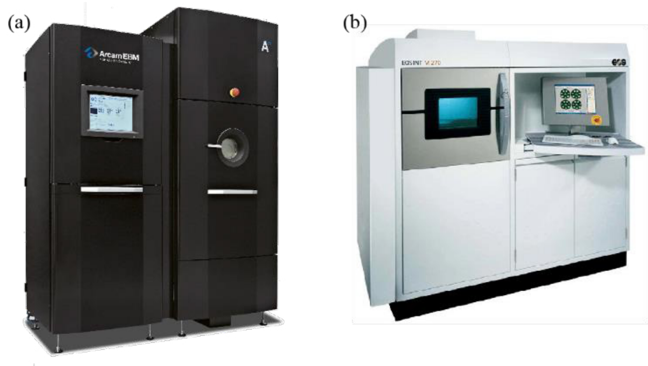

Fig. 2. (a) Arcam A2X; (b) EOS M270.

2.1. Arcam A2X

The A2X machine (Fig. 2a) consists of two high columns. That one on the left contains all the electronic and control components, while the right one contains the build chamber. Into the build chamber, the powder is spread in layers of 50 ÷ 200 μm by a rake on a build platform with the maximum dimensions of 210 mm x 210 mm and is melted with an electron beam. The electrons are emitted by a tungsten filament contained at the top of the electron gun, positioned at the upper part of the machine, right above the powder bed. The generated electrons are accelerated by an anodic potential of 60 kV till almost the speed of light. A series of magnetic coils adjusts the shape, the diameter and the position of the beam on the build platform. The current is controlled into the interval of 0 ÷ 50 mA, with a maximum beam power of 3000W.

The kinetic energy of the electron beam is transformed in heat when it reaches the build layer, so that the metal powder is melted [12].

To avoid the deflection of the electron beam, the entire construction process takes place in a vacuum environment, with a pressure of 0.005 mbar into the build chamber before the process starts. The EB-PBF is defined as a hot process because the building temperature can reach 1100 °C. This characteristic provides the possibility to process several metallic alloys.

2.2. EOS M270 Dual Mode

The EOSINT M270 Dual Mode (Fig. 2b) machine is equipped with a Ytterbium (Yb) fiber laser source that is used to melt metal powders with a continuous power up to 200 W, a spot of 100 μm, a layer thickness from 20 to 40 μm and a scanning rate up to 7000 mm/s in an inert atmosphere.

During the building process, the process chamber is filled with argon and the oxygen content is limited to 0.1% in order to restrict the reactivity of the metal powder. The building volume of the machine is 250 mm x 250 mm x 215 mm.

A recoater blade deposits one layer of fine metal powder on the building platform and the laser beam melts the region of the powder according to the 3D CAD geometry. Then the platform is lowered to the height of one- layer thickness and the build process is continued until completion of the part fabrication.

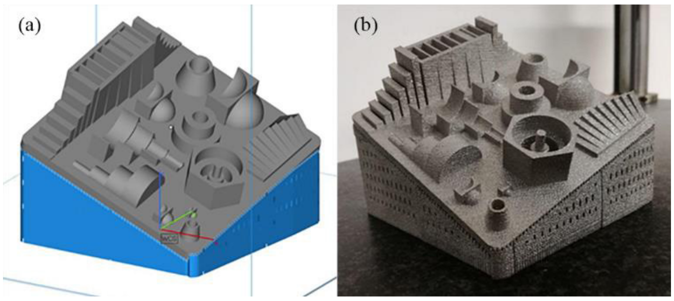

Fig. 3. (a) Part orientation in Magics software; (b) A2X replica.

3. Manufacturing of the replicas

For the comparison of the dimensional accuracy of the two machines and processes, Ti6Al4V material was used in the fabrication of a replica of the reference part.

3.1. EB-PBF production

The build job of the A2X machine was designed using version 21.11 of Materialise Magics software. The replica was positioned in the centre of the build plate. The orientation of the replica was selected to get an almost constant melting area along the building direction and a uniform temperature distribution. For this reason, the reference part was rotated about 23° with respect to both the x-axis and y-axis (Fig. 3a). Fragile and thin support structures were added at the bottom surface to support the building of the replica and to attach the part to build plate.

The standard set of process parameters for Ti-6Al-4V material provided by Arcam was used for building both the replica and the support structures using a layer thickness of 50 µm. The parameters for the contour and for the infill are listed in Table 1 and Table 2 respectively. A multibeam melting strategy was set for the contour, while a continuous melting strategy was used for the infill. The build job was processed by version 5.0 of the EBM build processor.

At the end of the process that took almost 26 hours, the entire build was left other 7 hours inside the EBM chamber for a cooling phase to room temperature preventing surface oxidations.

Table 1. Values of the process parameters employed for the contour in the fabrication of the titanium replica in the Arcam A2X machine.

Scan speed [mm/s]	Focus Offset [mA]	Beam Current [mA]	Number of spots	Number of contours	Hatch contours [mm]
850	6	5	70	3	0.29

Table 2. Values of the process parameters employed for the infill in the fabrication of the titanium replica in the Arcam A2X machine.

Speed Function	Focus Offset [mA]	Beam Current Max [mA]	Reference Length [mm]	Reference Current [mA]	Line Offset [mm]
45	25	20	45	12	0.2

Subsequently, the replica was cleaned using a sandblasting process using the same powder of the EBM process and an air pressure equal to 4 bar. The cleaning procedure was aimed at removing all residual powder partially sintered around the part surfaces. The cleaned part is shown in Fig. 3b. Finally, after cleaning, the supports were manually removed.

3.2. L-PBF production

The powder of Ti-6Al-4V alloy used for the EOSINT M270 replica is a gas atomized one by EOS GmbH, with a nominal density of 4.41 g/cm3. This titanium powder is very spherical and has a distribution with particle sizes of about 22.03 µm (d10), 33.35 µm (d50), 47.08 µm (d90) respectively. To reduce the thermal residual stresses between the substrate and the part, the building platform was kept at 100 °C. The part was built with an angle of 5° between any long edge and the recoater blade to prevent the deformation of the part (Fig. 4a). If the long edge was parallel to the blade, this can bump over the edge causing a vibration in the build volume and can lead to powder settlement which prevents recoating on subsequent sweeps, due to the high density of the metal powder. Considering scanning strategy, the direction of scanning is rotated of 67° between consecutive layers. Table 3 shows the process parameters used for the production of the replica. In the L-PBF process, different parameters can be used for the skin and the core [8], the contour and edges in order to improve the mechanical properties and dimensional accuracy of the built parts.

Table 3. Values of the process parameters employed for the fabrication of the titanium replica in the EOSINT M270 machine.

Parameters	**Skin**	**Core**	**Contour**
Scan speed [mm/s]	1000	1250	1250
Laser power [W]	150	170	120
Hatching distance [mm]	0.10	0.10	NA
Layer thickness [µm]	30	30	NA
Laser spot size [mm]	0.10	0.10	0.10

A correct design procedure for the L-PBF process requires a priori knowledge of the component's orientation on the building platform in order to insert a limited number of support structures as these increases both the time required for the production of the part and the time and complexity of post-processing operations. However, when the component is not optimized for the process, it becomes necessary to find an orientation able to reduce the possible deformations that may

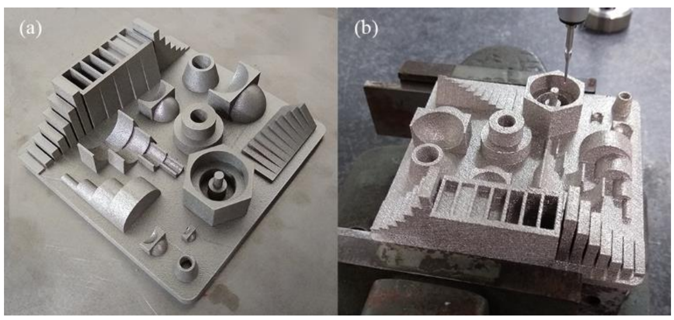

Fig. 4. (a) M270 replica; (b) CMM measuring phase of the A2X replica.

arise during construction.

In the L-PBF process, support structures are needed to prevent deformation and/or collapse of the part, to attach the part to the build platform and to conduct excess heat away from the part. Consequently, the optimization of the support structures is necessary to improve the sustainability and efficiency of the metal parts produced by L-PBF [9]. In this particular case, some of the geometric features of the reference part were designed with a specific slope. Given the large base surface, a correct realization of the replica would require the inclination of the part with respect to the building platform in order to reduce deformations. However, the inclination would lead to higher errors in the geometrical and dimensional accuracy of part features. The contour of the base was constructed attached to the platform to avoid the warping of the component during construction due to high thermal stresses caused by rapid solidification during the L-PBF process. The support structures were created and optimized by means of Materialise Magics software and the part fabrication took almost 16 hours.

4. Benchmarking results

4.1. CMM measurements

The two replicas were measured with a coordinate measuring machine (CMM) by Brown & Sharpe. The CMM model is the GLOBAL Image 07.07.07 that has a declared volumetric length measuring uncertainty MPE_E of 1.5 + L/333 µm according to ISO-10360/2 [13], where MPE is the acronym for Maximum Permissible Error and L is the measured length.

Following the methodology described by Minetola et al. [6], three replications of the measurement were carried out for the inspection of each replica (Fig. 4b). The average values of the three measurements were then considered in the analysis of the results. The dimensional accuracy of the compared PBF machines was evaluated taking into consideration the dimensional errors of the corresponding reference part replica. According to the ISO 286-1:1988 guideline [5], the deviation of the geometric features of each replica to their nominal value should be divided for the tolerance factor *i* that varies among different ranges of the ISO basic size (Table 4). The result of the division is the number *n* of times that the tolerance factor *i* fits into the dimensional deviation of the specific geometric feature. Table 5 shows the classification of the dimensional quality using the ISO IT grades that depend on the *n* value.

The number of tolerance unit n_j for the generic j-th dimension, that can represent the size of a geometric feature or the distance between features on the single replica, can be calculated by Equation 1 and attributed to the range of ISO basic sizes corresponding to the nominal dimension D_{jn}, while D_{jm} is the corresponding measured value of the generic j-th dimension. Within each interval of ISO basic sizes, depending on the number of replica dimensions fitting in the range, a certain distribution of the number of units n_j is obtained. The *n* value corresponding to the 95th percentile of that distribution is assumed as the maximum dimensional error of the AM system to define a unique IT grade for each range of ISO basic sizes. The IT grade is representative of the dimensional accuracy of the analysed machine for a specific range of feature size.

$$n_j = \frac{1000\left|D_{jn} - D_{jm}\right|}{i} \tag{1}$$

4.2. Discussion of results

Fig. 5 shows the comparison of the IT grade achieved by the two PBF machines for each range of ISO. It is evident that the L-PBF process is able to achieve better dimensional accuracy than the EB-PBF one.

Moreover, a thicker build layer was adopted on the Arcam A2X machine. Therefore, the superficial finishing and the accuracy of the EB-LPF process are worse than those of the L-PBF one, that generally uses finer metal powders.

Table 4. Ranges of ISO basic sizes and corresponding tolerance factor i.

Range		Basic sizes							
Above	D_1 (mm)	1	3	6	10	18	30	50	80
Up to and including	D_2 (mm)	3	6	10	18	30	50	80	120
Standard tolerance factor	*i* (µm)	0.542	0.733	0.898	1.083	1.307	1.561	1.856	2.173

Table 5. Classification of IT grades according to ISO 286-1:1988 [5].

Range		Standard tolerance grades													
Above	Up to	IT 5	IT 6	IT 7	IT 8	IT 9	IT 10	IT 11	IT 12	IT 13	IT 14	IT 15	IT 16	IT 17	IT 18
1 mm	500 mm	7*i*	10*i*	16*i*	25*i*	40*i*	64*i*	100*i*	160*i*	250*i*	400*i*	640*i*	1000*i*	1600*i*	2500*i*

Table 6. ISO IT grades for the traditional injection moulding process of ABS material.

Range		Basic sizes							
Above	D_1 (mm)	1	3	6	10	18	30	50	80
Up to and including	D_2 (mm)	3	6	10	18	30	50	80	120
Precision injection moulding [14]	IT Grade	12	11	11	11	12	12	12	12
Coarse injection moulding [14]	IT Grade	14	14	13	13	14	14	14	14

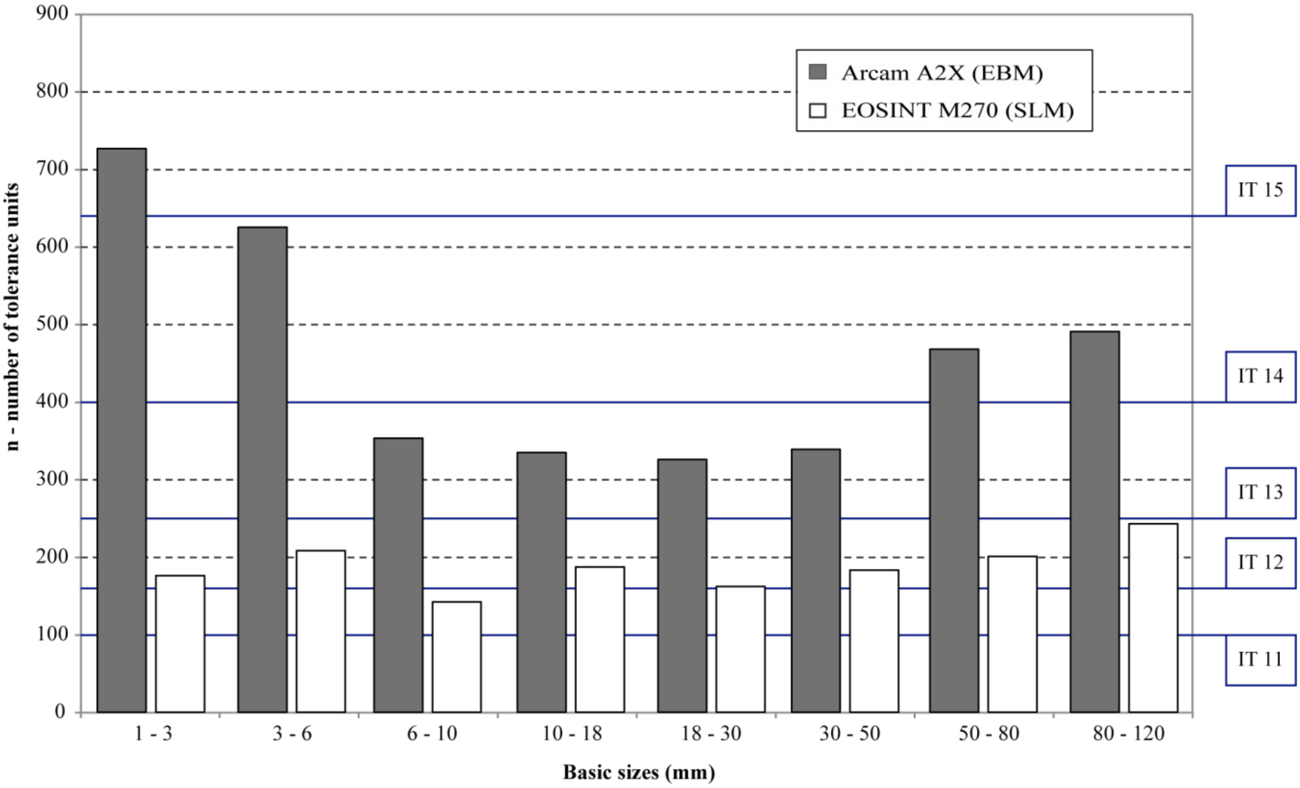

Fig. 5. Dimensional accuracy (95th percentile) of the compared PBF machines in terms of IT grades for different ranges of ISO basic size

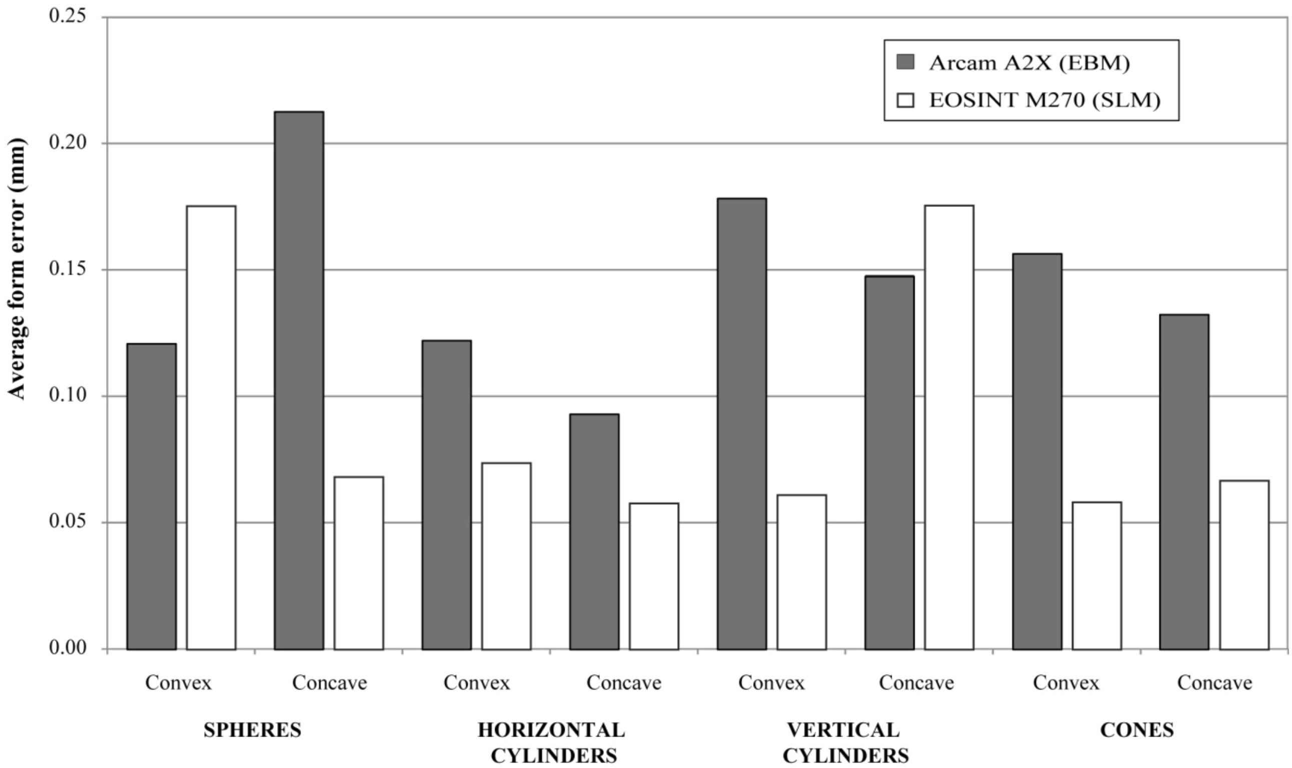

Fig. 6. Comparison of the PBF machines in terms of average form errors of the geometries of the reference part.

The replica fabricated by the EOSINT M270 machine has almost a constant quality with the IT12 grade recurring for all basic size ranges except for the 6-10 mm range, for which an IT11 grade is registered.

As regards the replica produced by the Arcam A2X machine, the worst accuracy is achieved for the smaller dimensions and ISO basic sizes up to 6 mm. A dimensional quality around IT15 is obtained for the smallest ranges of 1-3 mm and 3-6 mm. For intermediate dimensions between 6 and 50 mm, the Arcam A2X accuracy remains almost constant at a better IT13 grade. For bigger dimensions, the accuracy of the EBM replica decreases with a difference in one class, since features in the range above 50 mm have an IT14 quality. With the purpose of conveying to the reader a better idea about the PBF process accuracy, the traditional manufacturing processes that provide similar results are casting or forging operations for metals [15] and injection moulding for polymers.

The DIN 16901 guideline [14] of the German Institute for Standardization provides the admissible tolerances for different polymers for linear dimensions grouped by ranges that are very similar to the ISO ranges. The tolerances are provided by three different quality levels: coarse, fine and precision quality. For each of the three quality levels, the IT grade corresponding to the different ISO ranges can be derived from the DIN 16901 guideline. In fact, the number n of tolerance units (Table 5) can be calculated by dividing the admissible tolerance of Table 2 [14] of DIN 16901 by the tolerance factor i (Table 4). The results are included in Table 6 for the low-quality level of coarse accuracy and the top-quality level of precision engineering for injection moulded parts of ABS (Acrylonitrile-Butadiene-Styrene) material.

The average form errors of the simple shapes of the reference part are reported in Fig. 6. For each type of geometric feature (spheres, horizontal cylinders, vertical cylinders, and cones) the average deviation is separated for concave shapes and convex ones. The form errors confirm the higher accuracy of the replica fabricated using the EOSINT M270 machine. However, due to bigger deviations on the convex sphere of 8 mm diameter and on the vertical concave cylinder of 4 mm diameter, the average shape errors of the Arcam A2X system in Fig. 6 are lower for these types of geometries.

5. Conclusions

In this study, the dimensional accuracy of two PBF systems for metal materials was compared using ISO International Tolerance grades. The compared machines are an Arcam A2X for the EB-PBF process and an EOS EOSINT M270 for the L-PBF process. The comparison was carried out through CMM dimensional measurements of two replicas of a reference part that were fabricated with Ti-6Al-4V powders.

The EOSINT M270 outperformed the Arcam A2X with higher dimensional accuracy that can be attributed partly to the difference in the AM process, partly to the finer size of the Ti64 powder and partly to the smaller layer thickness adopted in the production of the L-PBF replica.

In the best case, a difference of one class of the ISO IT grades is obtained for dimensions in the range from 6 to 50 mm between the dimensional quality of the Arcam A2X replica and the one of the EOSINT M270 replica. The Ti64 replica processed by the laser source has a constant dimensional accuracy around IT12 for all dimensions fitting in the considered ISO ranges up to 120 mm. The accuracy of the replica processed by the electron beam source results in the IT13 class or worse, with smaller geometric features most affected by the coarser resolution.

As regards the shapes, except for two specific geometries, the average form errors of the replicas produced by the EOSINT M270 are included in the range between 0.05 and 0.10 mm. Most of the average form errors of the geometries of the Arcam A2X replica fit in the range 0.10 ÷ 0.20 mm.

However, despite the higher accuracy, the L-PBF process exposes the material to high thermal gradients, so laser melted parts have severe residual stresses. Because of the high process temperatures and slow cooling phase, EBM parts are not subjected to the issue of the residual stresses. In this work both reference part replicas were measured in the as-built state, so the dimensional accuracy refers to the layerwise process only. The EOSINT M270 replica was measured using the CMM prior to a stress releasing thermal treatment, with the part still attached to the build plate through the support structures.

The CMM measuring phase will be repeated for the L-PBF replica after the thermal treatment and after the wire electron discharge machining (WEDM) operation that is normally applied for the separation of the part from the build plate. On one side, the results of the new dimensional inspections will provide the accuracy for the EOSINT M270 replica at the end of its post-processing route. On the other side, the influence of the single post-processing operation will be investigated as well by comparing the CMM measurement results after each processing step.

References

[1] Calignano F, Manfredi D, Ambrosio EP, Biamino S, Lombardi M, Atzeni E, Salmi A, Minetola P, Iuliano L, Fino P, Overview on Additive Manufacturing Technologies. P Ieee 2017;105:593-612.
[2] Zhai Y, Lados DA, LaGoy JL, Additive Manufacturing: Making Imagination the Major Limitation. JOM 2014;66:808-816.
[3] Frazier WE, Metal Additive Manufacturing: A Review. Journal of Materials Engineering and Performance 2014;23:1917-1928.
[4] Santos EC, Shiomi M, Osakada K, Laoui T, Rapid manufacturing of metal components by laser forming. International Journal of Machine Tools and Manufacture 2006;46:1459-1468.
[5] ISO 286-1:1988 - ISO system of limits and fits - Part 1: Basis of tolerances, deviations and fit, International Organization for Standardization (ISO); 1988.
[6] Minetola P, Iuliano L, Marchiandi G, Benchmarking of FDM machines through part quality using IT grades. Procedia CIRP 2016;41:1027-1032.
[7] GrabCad, https://grabcad.com/library/benchmarking-of-additive-technologies-1. (Accessed 23rd April 2019).
[8] Ippolito R, Iuliano L, Gatto A, Benchmarking of rapid prototyping techniques in terms of dimensional accuracy and surface finish. CIRP annals 1995;44:157-160.
[9] Scaravetti D, Dubois P, Duchamp R, Qualification of rapid prototyping tools: proposition of a procedure and a test part. The International Journal of Advanced Manufacturing Technology 2008;38:683-690.
[10] Minetola P, Galati M, A challenge for enhancing the dimensional accuracy of a low-cost 3D printer by means of self-replicated parts. Additive Manufacturing 2018;22:256-264.
[11] Minetola P, Galati M, Iuliano L, Atzeni E, Salmi A, The Use of Self-replicated Parts for Improving the Design and the Accuracy of a Low-cost 3D Printer. Procedia CIRP 2018;67:203-208.
[12] Galati M, Snis A, Iuliano L, Experimental validation of a numerical thermal model of the EBM process for Ti6Al4V. Comput Math Appl 2019;78:2417-2427.
[13] ISO 10360-2:2009 - Geometrical product specifications (GPS) - Acceptance and reverification tests for coordinate measuring machines (CMM) - Part 2: CMMs used for measuring linear dimensions, International Organization for Standardization (ISO); 2009.
[14] DIN 16901 - Plastics mouldings: Tolerances and acceptance conditions for linear dimensions, Beuth Verlag GmbH; 1982.
[15] Violante MG, Iuliano L, Minetola P, Design and production of fixtures for free-form components using selective laser sintering. Rapid Prototyping J 2007;13:30-37.